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STRUCTURAL DESIGN CONSIDERATIONS IN THE MIRROR FUSION TEST FACILITY (MFTF-B) VACUUM VESSEL *

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ABSTRACT

The Lawrence Livermore National Laboratory has the primary national responsibility in the U.S. for developing the magnetic mirror approach to a fusion reactor. A goal of LLNL's magnetic fusion energy program is to provide the technology to develop a continuously operating fusion reactor. The heart of this reactor will be a plasma confined by magnetic field geometry and continuously sustained by injection of beams of energetic neutral atoms (such as deuterium). The highest priority in the Mirror program is to improve the energy gain factor, Q, the ratio of fusion energy produced to the energy input.

The Mirror Fusion Test Facility (MFTF) is a part of this effort scheduled for completion in FY '81. In view of favorable results from the Tandem Mirror Experiment (TMX) also at LLNL, the MFTF project is now being rescoped into a large tandem mirror configuration (MFTF-B), which is the mainline approach to a mirror fusion reactor. This paper concerns itself with the structural aspects of the design of the vessel. The vessel and its intended functions are described. The major structural design issues, especially those influenced by the analysis, are described. The objectives of the finite element analysis and their realization are discussed at length.

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1.0 Introduction

The confinement of high temperature plasma by means of magnetic mirrors[1] represents one of the basic concepts in plasma physics. Topologically, mirror confinement represents an "open" system, as opposed to "closed" magnetic systems such as the tokamak.

In an open system, such as a mirror machine (Figure 1), magnetic confinement operates both along and across the magnetic field. The magnetic field not only inhibits the diffusion of particles across the field lines to the chamber wall, but it also acts to inhibit their escape along the field lines. Longitudinal confinement, essential in an open device, is achieved here by the magnetic mirror effect, i.e. particles spiraling along the field lines are repelled from regions of increasing magnetic field--the mirrors--located at the ends of the confinement chamber. In a tandem mirror machine[2], magnetic mirror confinement of a hydrogenic plasma is enhanced by electrostatic confinement or plugging. Regions of high electrostatic potential are created at the ends of the machine, thus inhibiting the escape of ions from the central regions.

The structural integrity of the vessel is an important aspect of the technological objectives of MFTF-B. The eventual goal of the Mirror Fusion Program is to develop power reactors[3] to produce inexpensive and safe electric power. One of the objectives of MFTF-B is to learn to construct such large vessel systems which are comparable in size to those needed in fusion power reactors.

2.0 Description of the Vessel

The vessel which forms the vacuum envelope of the MFTF-B, is a long cylindrical structure comprising of three distinct sections (see Figure 2). At the two ends are the so-called "plug vessels", which are connected by a long center vessel of smaller diameter. Table 1 gives the dimensions of the vessels and their masses. The vessels are subjected to severe functional requirements.

The gravitational loads, other than the weight of the vessel structure itself, arise mainly from the 22 magnets mounted inside the vessel (Figure 3). Table 2 lists the masses of the various magnets used in MFTF-B. The inner twelve of the solenoid coils will be linked together with supporting structure in the direction of the longitudinal axis of the vessel. When all 12 coils are excited symmetrically, no force is exerted on the center vessel in which they are supported. However, in each end vessel, the yin-yang pair (a pair of interlocked C-shaped coils), the transition coil, and the outermost solenoid coil are tied together structurally, independent of the central solenoid stack, to minimize the axial compressive forces exerted on the vessel wall. These forces are transmitted to the vessel by a complex set of magnet hangers. In addition, the A-cell magnets are suspended independently from the rest of the magnets. Thus, there are five systems of magnets suspended inside the vessel, the two A-cell magnets on either end, the Yin-Yang, transition and solenoid system on each end and the central solenoid system. Table 3 shows the axial forces acting on the magnets, indicating a resultant force of 6.63 MN (1.49 x 10^6 lbs), the negative sign indicating a compressive force acting on the vessel. It may be noted that this compressive force is in addition to that arising out of the vacuum in the vessel, which amounts to 9.79 MN (2.2 x 10^6 lbs). Asymmetric excitation of the coils is also considered in the design, so net longitudinal forces on the center vessel must be taken into account. The massive nature of the magnets, makes them important elements in the seismic analysis of the system. While they are structurally far more rigid than the vessel itself, the oscillation of these magnets in rigid body modes, dominates the first few modes of the system.

The vessel must also provide for the mounting of all equipment for forming, heating, maintaining and diagnosing the plasma. There are three neutral beam assemblies on each end vessel, and twelve re-entrant neutral beam lines in the center vessel, each of which has a mass of 18.18 Mg (40,000 lbs). The neutral beam domes incorporated into the MFTF vessel as precisely aligned mounting platforms for source modules will be replicated with fewer mounting ports in the west end of the vessel. There are more than 300 penetrations in the vessel for neutral beam injection, ECRH heating, streaming guns, getter diagnostics, and vacuum, cryogen, D_2 gas, and cooling water services. The total equipment mass to be supported is 2410.0 Mg (5.3 x 10^6 lbs), in addition to an estimated vessel mass of 886.0 Mg (1.95 x 10^6 lbs).

3.0 Structural Problems and Design Philosophy

A major design consideration is the desirability of making the solenoid coils easly removable for maintenance. Two schemes were considered. The first was to make the center vessel of short cylindrical modules, with six modules each containing two solenoid coils. The second was to make the center vessel of integral construction, with short slotted rectangular extensions through which each of the twelve central solenoid coils is inserted. The significant advantage of the modular concept is the greater flexibility it affords from a project scheduling standpoint, since it permits the simultaneous assembly of all of these modules, and at the same time to be tested individually before final assembly. From a structural point of view, there is not much to choose from between the two concepts, since the degree of difficulty in installing internal structure and solenoid-to-vessel support system appears to be equal in either of the concepts. A decision has been made to build the center vessel using the modular concept.

An important design decision impacting other members of the project team was the method of mounting the two ends of the vessel. The longitudinal forces on the vessel system, in addition to the magnetic forces, include a net atmospheric compressive load of 9.79 MN (2.2×10^6 lb), and forces arising from contraction and expansion of the vessel shell (thermal contraction of the LHe-cooled magnets will be partially accommodated by their suspension system). In order to alleviate the thermal stresses in the longitudinal direction, consideration was given to mounting the end vessels on longitudinally floating supports with the magnetic and atmospheric loads carried by the center vessel in column compression. Analysis to date has shown, however, that fixed vessel leg supports on either end of the MFTF will, in combination with the center vessel, handle the longitudinal loads in bending, and will be compliant enough to prevent overstressing of the vessels by thermal changes. The vessel support legs must, of course, withstand the dynamic loads, during a prescribed seismic excitation at the Livermore site.

The predominant loads on the vessel are those arising from the masses of the magnets and the equipment mounted on the surface. It is therefore, almost intuitively obvious that the proper design of the vessel is one in which the vessel skin is subjected mainly to vacuum and magnetic loads whereas the gravitational loads are for the most part borne by stiffeners in the circumferential direction. Thus, the load path from the magnets to the vessel support legs, passes directly through the circumferential stiffening rings. There are also stringers to withstand the previously mentioned longitudinal forces on the vessel system. One of the objectives of the finite element analysis is to determine the changes in the stiffening pattern of the existing MFTF vessel to withstand the higher loads in the MFTF-B Configuration. In addition, the design of the magnet hanger system in the MFTF-B configuration is more complex involving as it does a system of 22 magnets in place of the single Yin-Yang pair in the MFTF. The alignment of the magnets in the operating condition demands that the contractions and deformations due to operating loads be precisely evaluated and allowed for while installing the magnets.

4.0 Finite Element Modeling and Results

The modeling of the vessel has been done on a version of the SAPIV finite element code in use at LLNL. The version at the Laboratory uses an algorithm called the GPS algorithm[4] which yields a minimum bandwidth of the stiffness matrix. The eigenvalue extraction method used is the subspace iteration method, which can be interpreted as a repeated application of the Ritz method[5] in which the computed eigenvectors from one step are used as the trial basis vector for the next iteration until convergence to the required eigenvalues and eigenvectors is obtained. In addition to the SAPIV Code, pre-and post-processors are utilized to generate the mesh, and draw pictures of the deformed shape of the vessel respectively. While the SAPIV Code is a 1960's vintage structural analysis code, the incorporation of the above features makes the use of the code for a reasonably large problem such as the MFTF-B vessel, less painful than it would otherwise have been. The entire system was modeled using 1100 nodes, 1250 beam elements, and 500 plate elements. Figure 4 shows one-half of the vessel magnet system. The objectives of the model were to:

- Try to attain an optimal minimum weight design so that significant cost savings can be attained by reducing overall weight of vessel.

- Determine adequacy of structural design.
- Compute stresses at critical locations.
- Supply loads at footing pads to LLNL Conventional Facilities group, and as preliminary design parameters, to the vessel manufacturers.
- Supply loads at magnet hangers to the vessel manufacturer.
- Decide whether one end of the vessels should be mounted on floating or fixed supports and design the supports to handle longitudinal loads in bending and so that they are compliant to permit thermal changes in the vessel.

The vessel is modeled to a greater degree of detail than the magnets, which are, for the most part treated as masses, with their structural properties only grossly represented.

There are two major aims in this process. In the static analysis, the aim is to determine locations of greatest stress, and alter the structure in those areas as required, so that the load paths are adequate with regard to stresses and deflections. In some instances, deflections which are structurally tolerable must nevertheless be reduced to satisfy operational requirements on alignment. In the dynamic analysis, the modes and frequencies of the system are first determined. Fundamental frequencies at or below the peak of the response spectrum curve are raised by alteration of the structure. In the structure as now conceived, the fundamental frequency is 4.0 Hz. The fundamental modes are dominated by the oscillation of the magnets, mainly as rigid bodies. A lesser proportion of the energy in the modes is in the vessel itself. One method of raising the fundamental frequencies is therefore to stiffen the magnet hangers. This is presently under study. The response spectrum analysis is then carried out, amplitudes are calculated, and the structural properties are further altered to "tune" the total response so that allowable stresses under seismic loading are not exceeded. Throughout, the aim has been to achieve these goals with maximum economy of structure, in order to arrive at a vessel design both structurally sound and cost effective.

At this time we have completed one pass through the above process and changes are being incorporated in the model to reflect decisions already made. In the next phase of the analysis it is proposed to do more detailed analysis at selected locations on the vessel where, for instance, the beam line assemblies are mounted. The present thinking is that additional scaffolding will be needed to support these neutral beam assemblies. The detailed models will be used to evaluate the need for the above.

The computing system we are using at LLNL is the Magnetic Fusion Energy Computing Center (MFECC) which is a national network connected to all the Plasma Physics Laboratories in the United States. Eventually, the Computing Center will be connected via satellite to centers in Germany, and Japan. The interactive nature of the MFECC system makes it convenient to run large size problems on programs such as SAPIV.

Conclusions:

The structural analysis of the MFTF-B vessel is an important element of the MFTF-B project. This paper has described the objectives of the analysis, some decisions already reached as a result of the analysis, some of the assumptions made, and finally, the results. The design phase of the MFTF-B vessel will essentially be complete early in 1982, at which time construction on the new vessel will begin.

References:

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TABLE 1

MFTF-B VACUUM VESSEL

Dimensions	
Overall Length m(ft)	66.0 (216.54)
Diameter of End Plug m(ft)	10.6 (34.78)
Length of End Plug m(ft)	20.0 (65.62)
Diameter of Center Vessel m(ft)	8.0 (26.25)
Length of Center Vessel m(ft)	23.0 (75.46)

Masses	
East End Vessel Mg(lbs)	348. (766,000)
West End Vessel Mg(lbs)	348. (766,000)
Center Vessel Mg(lbs)	174. (382,800)
Two Transition Sections Mg(lbs)	16. (35,200)
Total Mg(lbs)	886. (1,950,000)

TABLE 2

MFTF-B MAGNET MASSES

Type	Quantity	Mass Mg(Lbs)
A-Cell	2	455.0 (1.0×10^6)
Yin-Yang Pair	2	682.0 (1.5×10^6)
Transition	2	182.0 (0.4×10^6)
Solenoids	14	209.0 (0.46×10^6)

TABLE 3

MFTF-B MAGNETIC LOAD SUMMARY
Magnetic Field in the Center B_c = 1 Tesla

COIL	AXIAL FORCE	
	MN	10^3 lb.
A-Cell (M_3)	-4.67	-1050.
Yin Yang Pair		
M_2	-10.32	-2,320.
M_1	1.67	376.
Transition Coil (T1)	-1.67	-375.
Solenoid (S7)	8.36	1,879.
TOTAL	- 6.63	-1,490.

TABLE 4

MASSES OF AUXILIARY EQUIPMENT MOUNTED ON VESSEL

	Mgs	Lbs
Diagnostics	273.	(600,000)
Beam Line Assemblies	273.	(600,000)
Cryopanels	77.	(170,000)
Neutral Beam Injectors	91.	(200,000)
Others & Miscellaneous	195.	(430,000)
TOTAL	909.	(2,000,000)

MFTF-B TANDEM MIRROR FACILITY

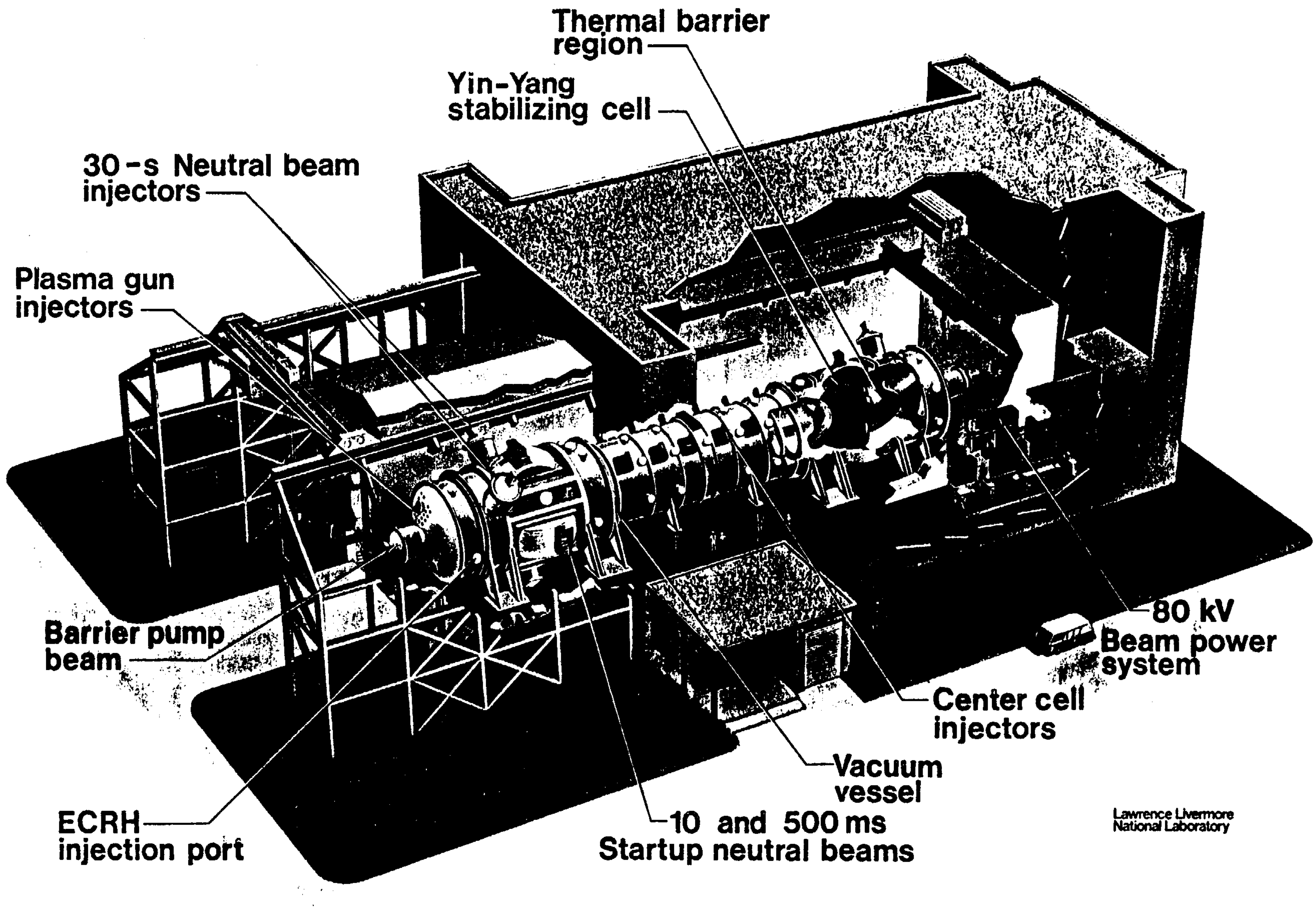

FIGURE 1: MFTF-B TANDEM MIRROR FACILITY

MFTF-B VACUUM VESSEL AND MAGNETS

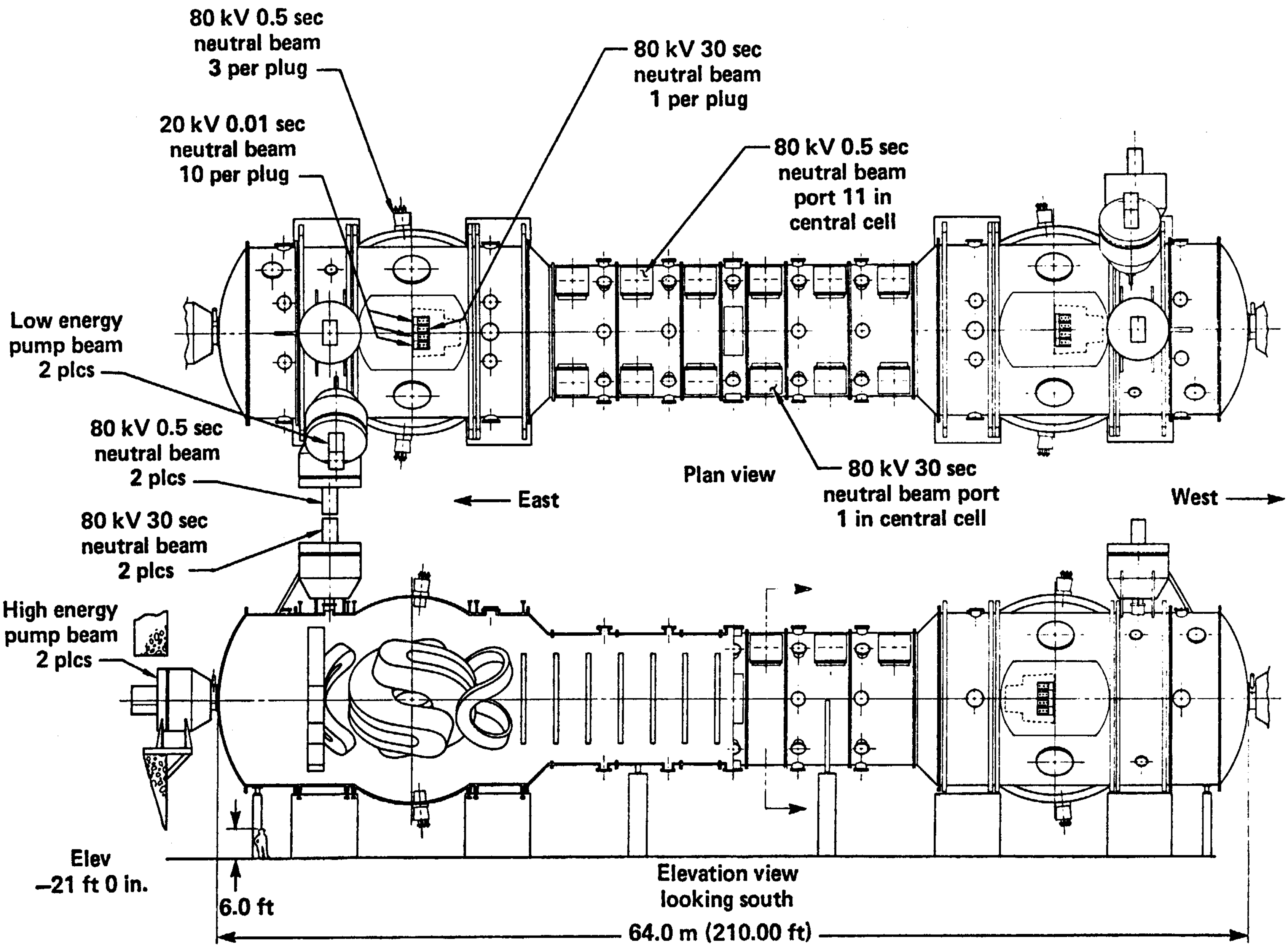

FIGURE 2

MFTF-B MAGNET ARRAY

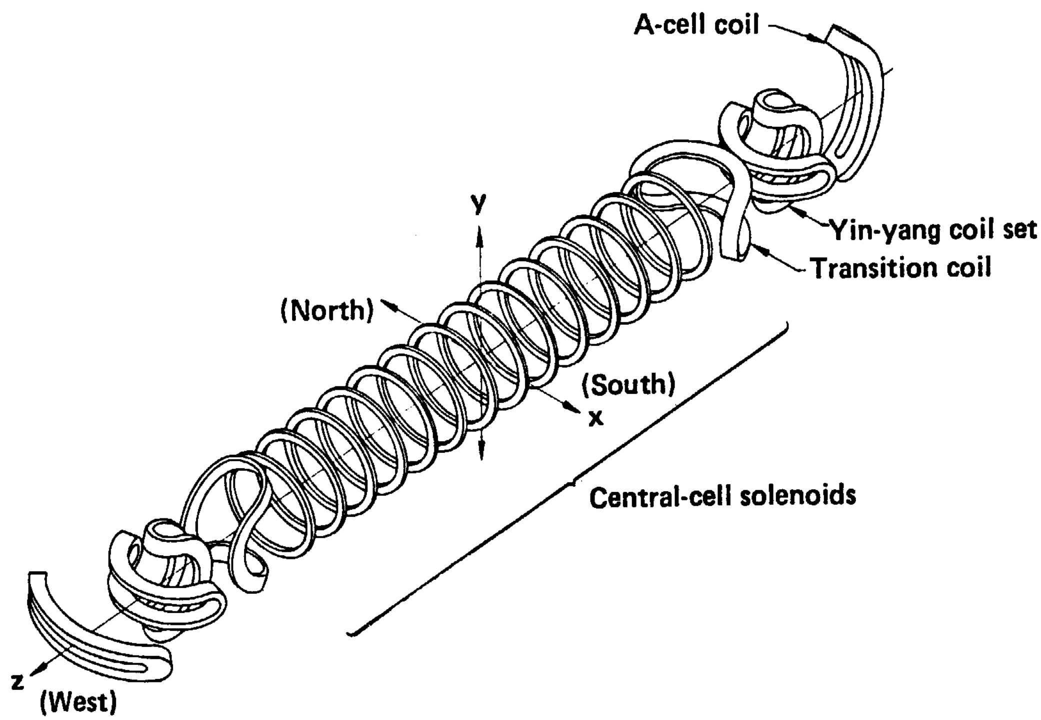

FIGURE 3 - MFTF-B MAGNET ARRAY

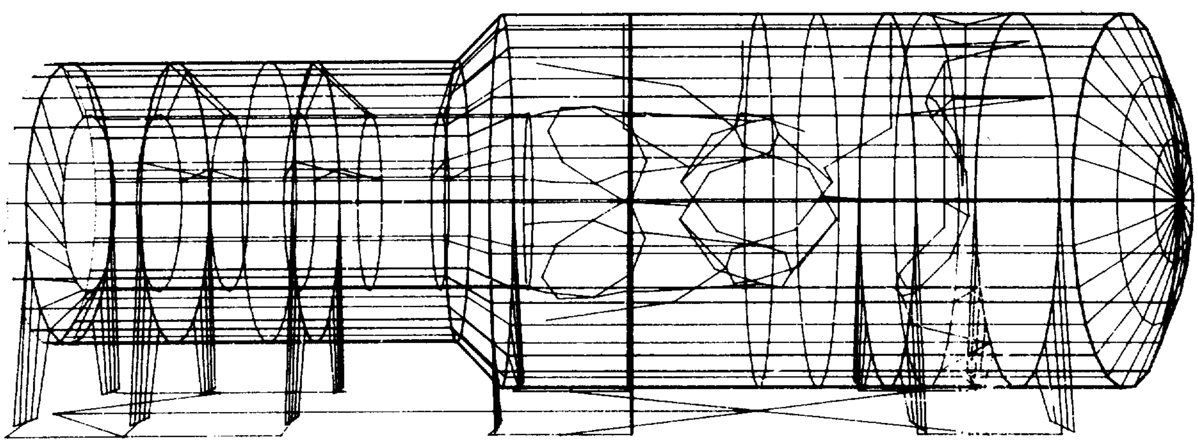

FIGURE 4: MFTF-B SAPIV FINITE ELEMENT GRID